CLNS 02/1812
WSU-HEP-0210

A Method for Measuring Emittance in e^+e^- Colliding Beams

D. Cinabro,[1] K. Korbiak*,[1] M. Billing,[2] N. Mistry,[2] D. Rice,[2] and D. Rubin[2]
[1]*Wayne State University, Detroit, MI 48202, USA*
[2]*Cornell University, Ithaca, NY 14853, USA*

(Dated: 4 December 2002)

Abstract

We have developed techniques that allow simultaneous measurement of the spatial size of the luminous colliding beam region and the angular spread of beams in collision using $e^+e^- \to \mu^+\mu^-$ events. These are demonstrated at the CLEO interaction point of the Cornell Electron-Positron Storage Ring, CESR, taking advantage of the small and well understood resolution of the CLEO tracking system. These measurements are then used to extract the horizontal beta, horizontal emittance and the vertical emittance and search for dynamic effects at CESR.

PACS numbers: 29.27.Fh

* Present address University of Michigan, Ann Arbor, MI 48109, USA

The measurement of the emittance of colliding beams is a difficult and important problem as many methods are destructive or disruptive to the beams or involve extrapolation using a theoretical accelerator transport matrix [1]. Here we present a method that relies on the tracking system of a high energy physics experiment done while the beams are producing luminosity without disruption or use of a transport matrix. The basic technique is to select an ensemble of $e^+e^- \to \mu^+\mu^-$ events with which we simultaneously measure the size of the luminous region and the intrinsic angular spread of the outgoing particles. At CESR and CLEO the resolution is precise enough that we can extract the the horizontal beta at the interaction point, β_x^*, the horizontal emittance, ϵ_x, and, combined with our previously described technique for measuring vertical beta at the interaction point, β_y^* [2], the vertical emittance, ϵ_y.

Assuming that dispersion and coupling are negligible, the beam parameters β_x^*, β_y^*, ϵ_x, and ϵ_y are related to the physical observables σ, the Gaussian width of the beam at the interaction point, and σ', the Gaussian width of the angular spread of the beam at the interaction point, by the following equations:

$$\sigma_x = \sqrt{\beta_x^* \epsilon_x} \tag{1}$$
$$\sigma_y = \sqrt{\beta_y^* \epsilon_y} \tag{2}$$
$$\sigma'_x = \sqrt{\epsilon_x / \beta_x^*} \tag{3}$$
$$\sigma'_y = \sqrt{\epsilon_y / \beta_y^*}. \tag{4}$$

A simultaneous measurement of both σ and σ' in the collision region would yield measurements of β^* and ϵ via the obvious algebraic manipulation.

Our previous work has shown how the size of the luminous region can be measured using $e^+e^- \to \mu^+\mu^-$ events [2]. Briefly a fiducial box is centered on the measured center of the luminous region. The average positions of tracks passing through the box are used to measure the size and shape of the luminous region. Tracks that pass through the box nearly perpendicular to one of the sides are most useful for making a measurement. At the CESR-CLEO interaction point the luminous region is roughly 7 μm high and 300 μm wide. Thus we select more useful tracks for the horizontal measurement than the vertical. We have previously used this technique to measure β_y^* and observe the hourglass effect at the CESR-CLEO interaction point [2].

We measure the angle between the projected μ^+ and μ^- tracks by considering the sum of the momenta of the two tracks divided by the beam energy to obtain a vector. If the two tracks are coming from the same point and have nearly the same momentum as the beam this vector is equivalent to the minor arc between the colliding tracks, given by $E_{\rm beam} \sin\theta$, where θ is the central angle between the colliding tracks. This angle is small and we approximate $\sin\theta$ by θ. We then define the angle between the two tracks in the horizontal projection as the horizontal momentum sum divided by beam energy and similarly in the vertical direction. Schematically this is shown in Figure 1.

A crossing angle between the beams causes the distribution of the angle to have a mean different from zero, an angular spread of the beam, σ', gives an intrinsic underlying width, and detector momentum resolution broadens the distribution.

CESR has been described in detail elsewhere [3]. All the data used in this measurement were taken at an e^+e^- collision energy of 10.58 GeV with bunch currents in the range of 2.5 to 7.0 mA over a four month period in late 1998 and early 1999. The CLEO detector has also

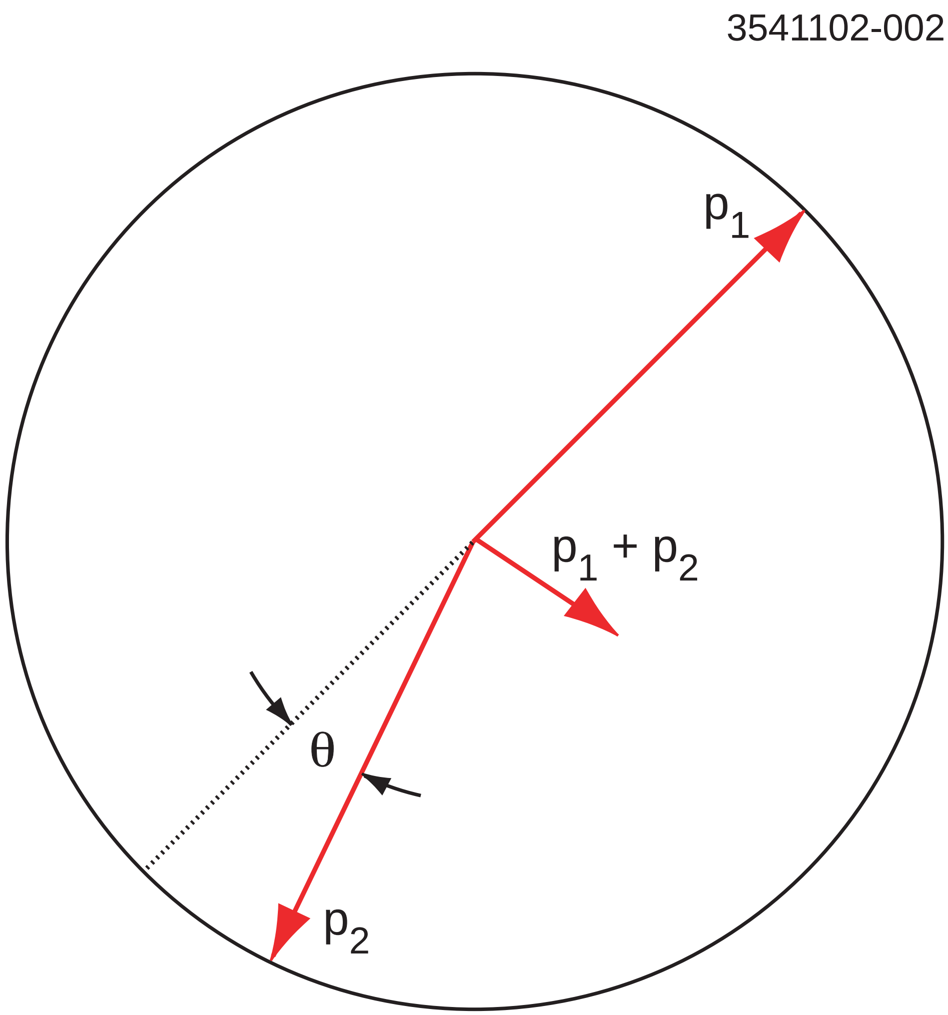

FIG. 1: In $e^+e^- \to \mu^+\mu^-$ the momentum sum of the two tracks is related to the angle between the two tracks. It gives the minor arc length which is approximately $E_{\text{beam}}\theta$.

been described in detail elsewhere [4]. All of the data used in this measurement are taken in the CLEO II.V configuration which includes a silicon strip vertex detector (SVX) which is crucial to the measurement of the size of the luminous region. This detector consists of three layers of silicon wafers arrayed in an octagonal geometry around the interaction point. The first measurement layer is at a radius of 2.3 cm and the wafers are read out on both sides by strips which are perpendicular to each other. The readout strips have a pitch of about 100 μm; with charge sharing, the detector has an intrinsic per-point resolution of better than 20 μm both longitudinally and in the plane transverse to the beam direction. The rest of the tracking system consists of a small 10 layer drift chamber, and a large 51 layer drift chamber which has an outer radius of 1.5 m. The tracking system is in a 1.5 Tesla magnetic field provided by a superconducting solenoid.

$e^+e^- \to \mu^+\mu^-$ events are easily selected in CLEO by choosing events with two and only

TABLE I: CESR beam parameters in the limit of zero bunch current.

Parameter	Value (μm)
β_x^*	1.1996×10^6
β_y^*	17900
ϵ_x	0.21
ϵ_y	0.0010

two tracks each with momentum near the beam energy and a small energy deposit in the electromagnetic calorimeter. We chose tracks with 20 or more hits in the main drift chamber, and at least two silicon vertex detector hits in the transverse and longitudinal views. We require that the tracks have opposite charge and that those used for the measurement of the luminous region have at least three silicon vertex detector hits in one of the two views. Each point for measuring the σ' is based roughly on 7000 events for σ'_x and σ'_y 2000 events.

The expected beam parameters for CESR for the data discussed in this paper are given in Table I. All the parameters in Table I are given in the limit of zero bunch current. Our measurements were taken over a long time, about four months of CESR and CLEO running, and under many different machine conditions. Thus we expect only rough agreement with the parameters given in Table I, but we should be sensitive to dynamic effects caused by the non-zero bunch currents. The horizontal β^* and ϵ are expected to depend primarily on the beam current, while the vertical ϵ is expected to be influenced more by the measured luminosity over beam current (the specific luminosity). Therefore we present measurements in the horizontal direction as functions of bunch current, while measurements in the vertical are presented as functions of specific luminosity. We have previously observed that β_x^* is reduced by roughly a factor of two in colliding beam conditions due to the dynamic beta effect [5]. Dynamic effects are also expected to produce a larger ϵ_y and a smaller β_y^* and β_x^* than given in Table I.

To be able to measure the angular spread of the colliding beams the momentum resolution must be well understood. We study CLEO's momentum resolution with a simulated sample of $e^+e^- \to \mu^+\mu^-$ events with no momentum spread in the incoming beam particles. Recent examples show that, for high momentum tracks, the simulation of the tracking accurately models the data [6][2]. The resolution on the angle between the μ^+ and the μ^- depends on global properties of the event such as the pattern of hits in the transverse and longitudinal views of the SVX. More hits improves the resolution and the $r\phi$ hits primarily effect the resolution transverse to the beam, while z hits effect the longitudinal resolution. Thus the data are divided according to the SVX hit pattern. For each sub-sample, the resolution is parameterized as

$$A + B/Nhits = \text{Resolution} \tag{5}$$

where $Nhits$ is the total number of tracking hits on both tracks. We determine the width of the momentum resolution as a function of $Nhits$, by selecting on a range of $Nhits$ and performing a one dimensional fit to a Gaussian plus a flat background to account for events not coming from beam collisions, mainly cosmic rays. To determine A and B for each SVX hit pattern, we fit the two dimensional distribution of resolution width versus $Nhits$. This gives us a set of A's and B's and combined with the observed SVX hit pattern and number of tracking hits we determine the resolution for each data event. The resolutions we extract

on the angle between the μ^+ and μ^- is better than 1 mrad in both the vertical and horizontal directions for the highest number of tracking hits and SVX hits and up to 3 mrads for the worst case.

We then fit the two dimensional data distributions of angular width versus number of tracking hits for each SVX hit pattern with a width that is quadratic sum of the resolution piece determined from the simulation as described above and an extra contribution due to the underlying angular width of the colliding beams. We note that the means of the angular distributions are consistent with the known crossing angle, 2.0 mrads in the horizontal and none in the vertical, with an accuracy of better than a 0.01 mrads. The underlying width is then the weighted average of the fitted underlying widths over the SVX hit patterns. Systematic uncertainties on the extracted angular width of the colliding beams are applied by doing the data fits again with the values for the A and B parameters of the resolutions varied up or down in concert by one standard deviation based on the results from the simulation. Typically this represents a variation of 0.2–0.4 mrad. We also repeat the analysis using only the events with the largest number of tracking hits with the best resolution and see negligible changes.

We are not sensitive to the vertical width of the luminous region. Our resolution on the size of the luminous region is about 30μm while our earlier observation showed that the underlying width is about 7μm. We take the observed vertical width to be the resolution on the horizontal width, and this agrees well with the prediction of the simulation. For this reason, dynamic measurements of β^*_y cannot be extracted. A constant measured value, $\beta^*_y = (17910 \pm 170)\mu$m [2], is used in this analysis to extract ϵ_y.

Figures 2 and 3 show the horizontal size and angular spread, of the luminous region respectively, as functions of bunch current. These are after the resolutions discussed above have been taken out. Note that these are not the beam parameters but the result of the colliding beams. The size is a factor of $\sqrt{2}$ smaller than the beam size due to the overlap of the two beams producing the luminosity, and the angular size is a factor of $\sqrt{2}$ larger than the angular beam spread due to the incoherent collision of the two beams producing the luminosity. Figure 4 shows the width of the vertical angular spread of the luminous region as a function of specific luminosity. From this data and algebraic manipulation of Equations 1, 2, 3 and 4 and the fixed β^*_y discussed above we extract β^*_x, ϵ_x and ϵ_y.

The extracted β^*_x is shown in Figure 5. This result agrees well with our expectations based on a previous analysis done which observed the dynamic beta effect [5]. The expectation was $\beta^*_x = 1.2$m reduced by roughly a factor of two. Here we see a $\beta^*_x \approx 0.6$m. The extracted horizontal emittance as a function of specific luminosity is displayed in Figure 6. We expected an $\epsilon_x = 0.21\mu$m-rad while we extracted an $\epsilon_x \approx 0.3\mu$m. These results again agree well with our expectation. We do not clearly see any dynamic effects. We also expect an extracted vertical emittance of $\epsilon_y = 0.0010\mu$m-rad. We extract an $\epsilon_y \approx 0.0030\mu$mrad. Our extracted value agrees with an earlier observation of $\epsilon_y = (0.0070 \pm 0.0054 \pm 0.0019)\mu$m-rad [2] and with values calculated based on the observed luminosity and the best possible theoretical estimates of the other beam parameters. This extracted vertical emittance, shown in Figure 7 appears to have dynamic effects. When a fit to a first order polynomial is applied to this data we see a slope that is significant at only the 2.4 standard deviation level, which we do not claim as significant. We observe no visible dynamic effects on vertical emittance although the data are suggestive.

These methods can also be applied to observe the beam energy spread which results in a mismatch of the longitudinal momenta of the two tracks in these events. Our resolution

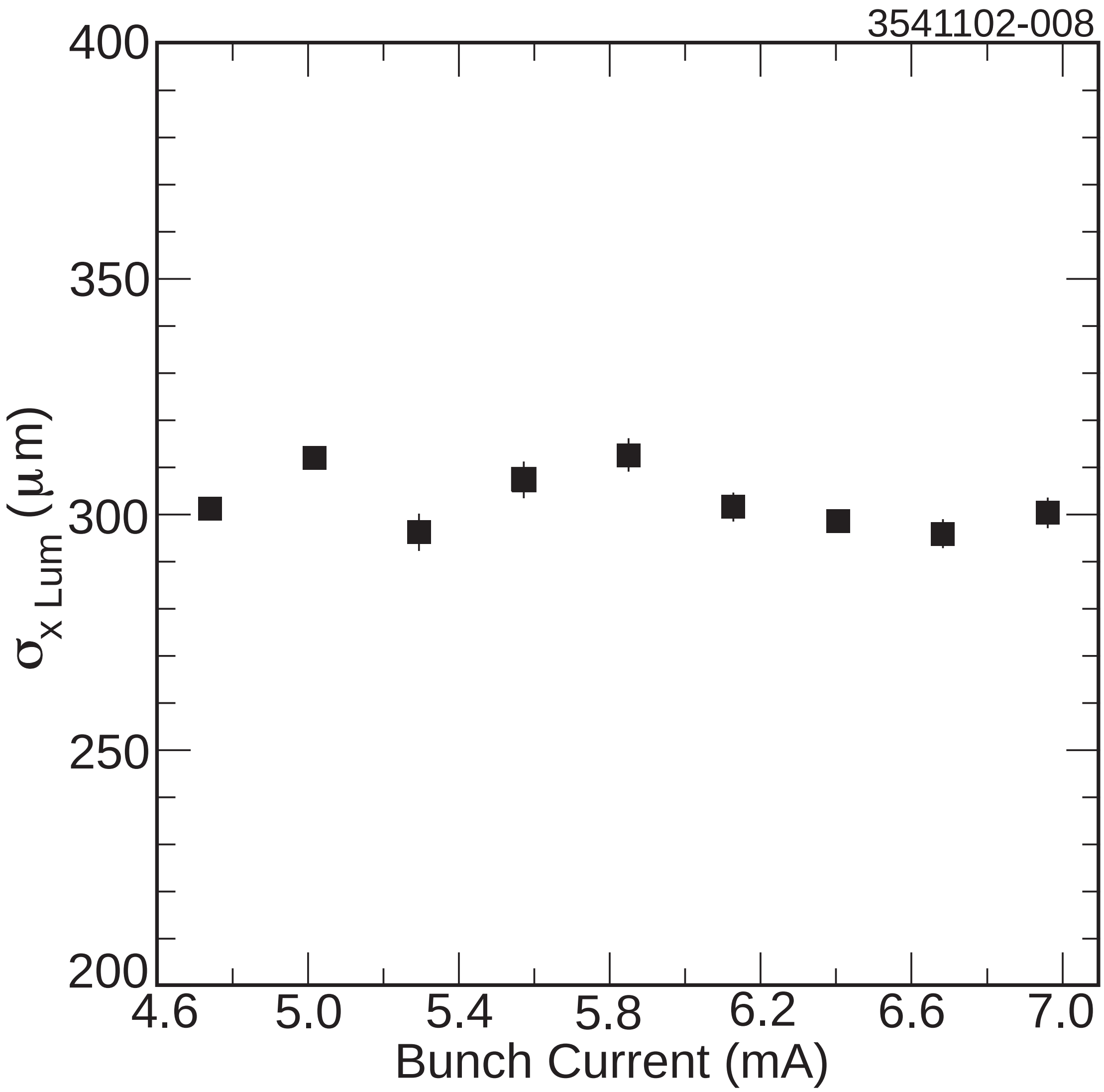

FIG. 2: The Gaussian horizontal width of the luminous region as a function of bunch current.

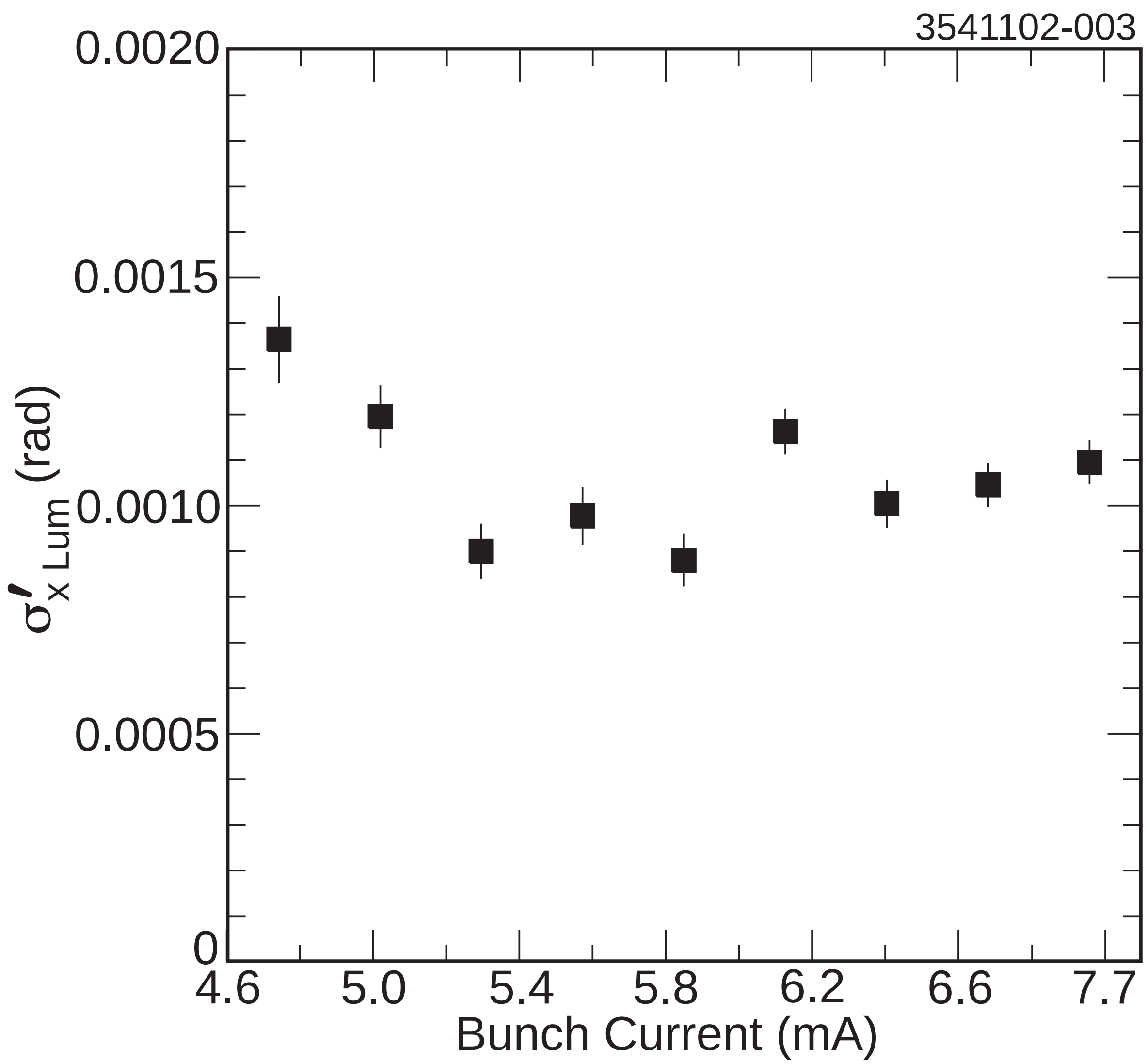

FIG. 3: The horizontal width of the angular distribution of the luminous region as a function of bunch current.

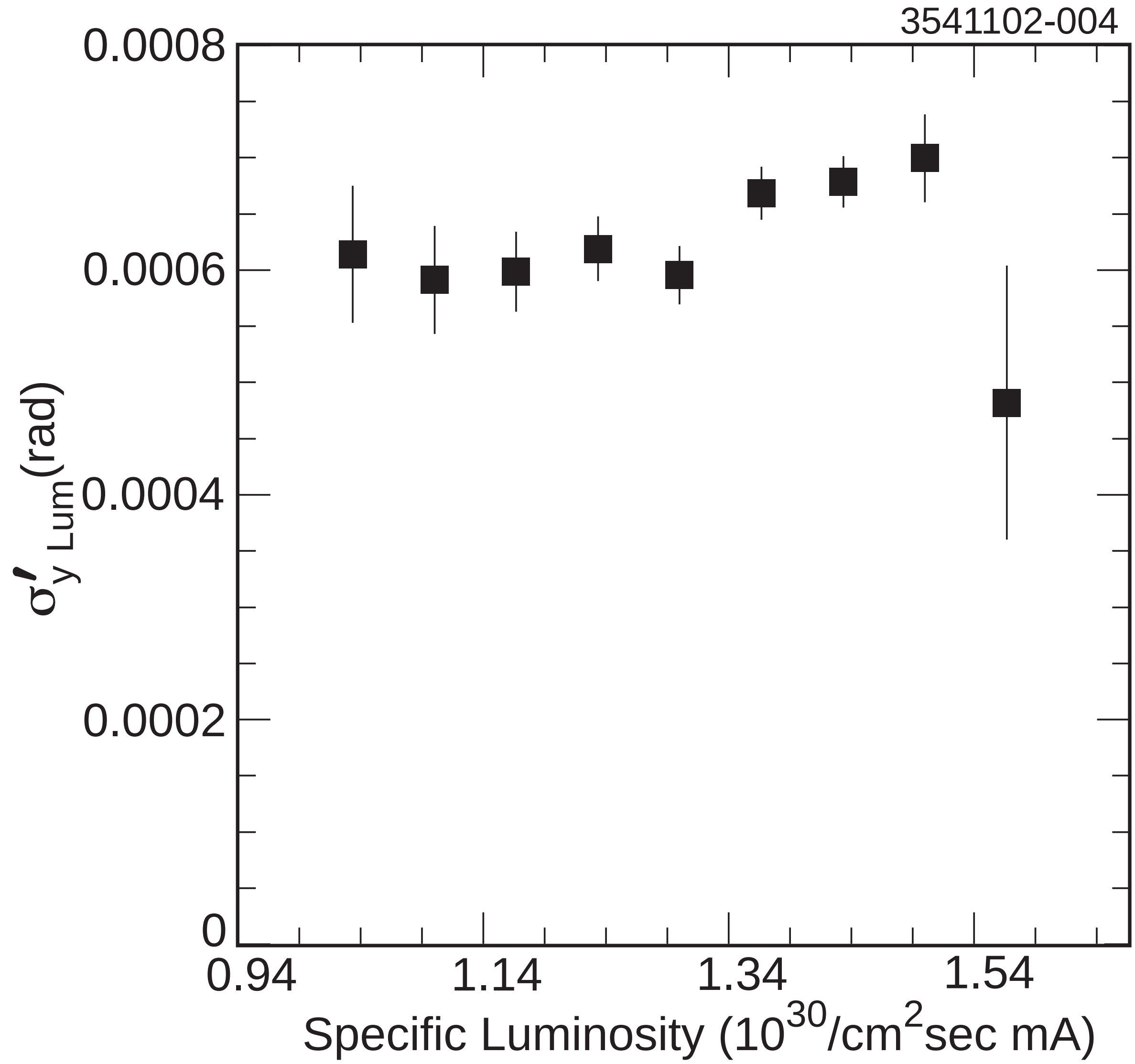

FIG. 4: The vertical width of the angular distribution of the luminous region as a function of specific luminosity.

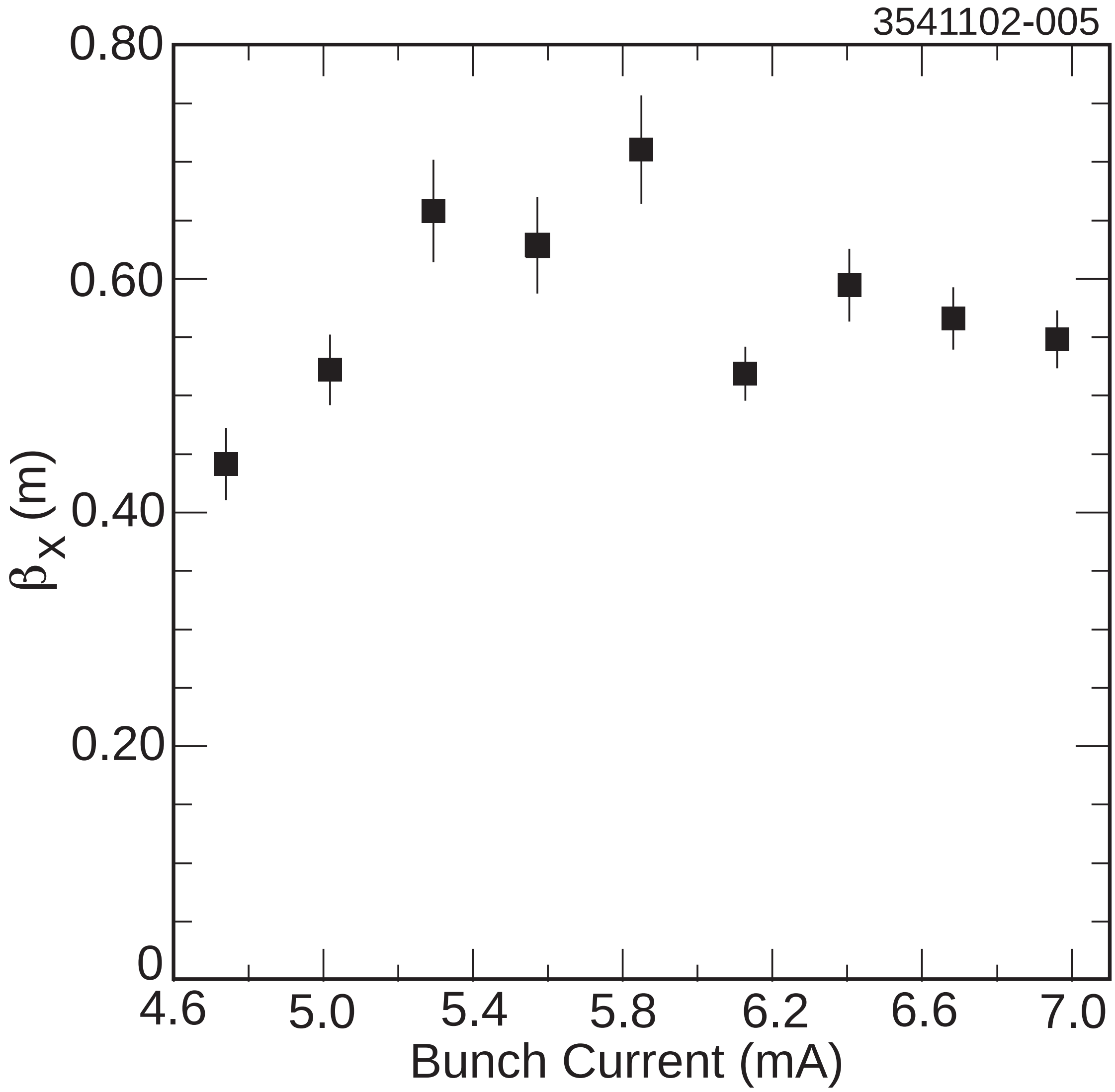

FIG. 5: The extracted horizontal beta as a function of bunch current.

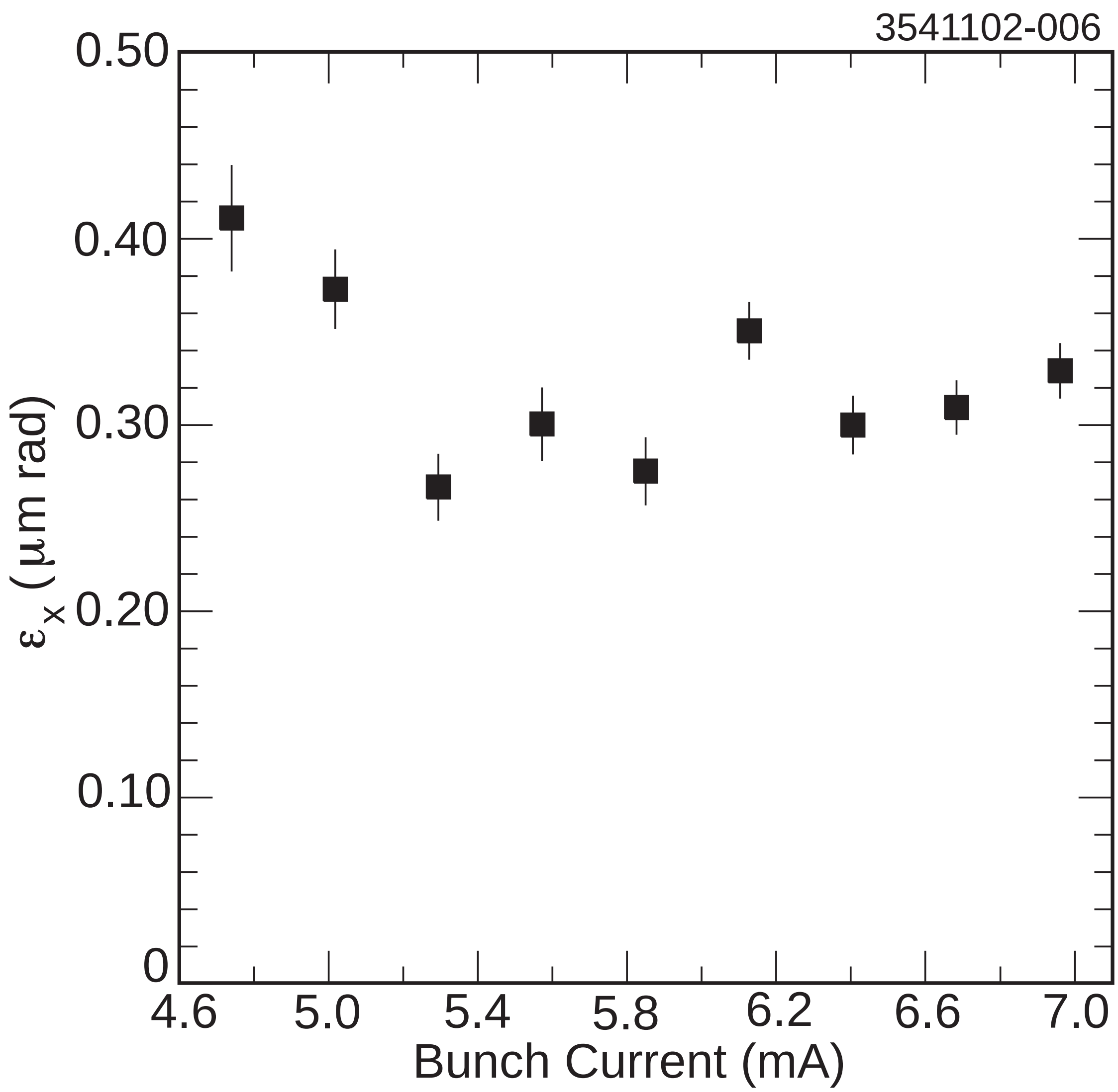

FIG. 6: The extracted horizontal emittance as a function of bunch current.

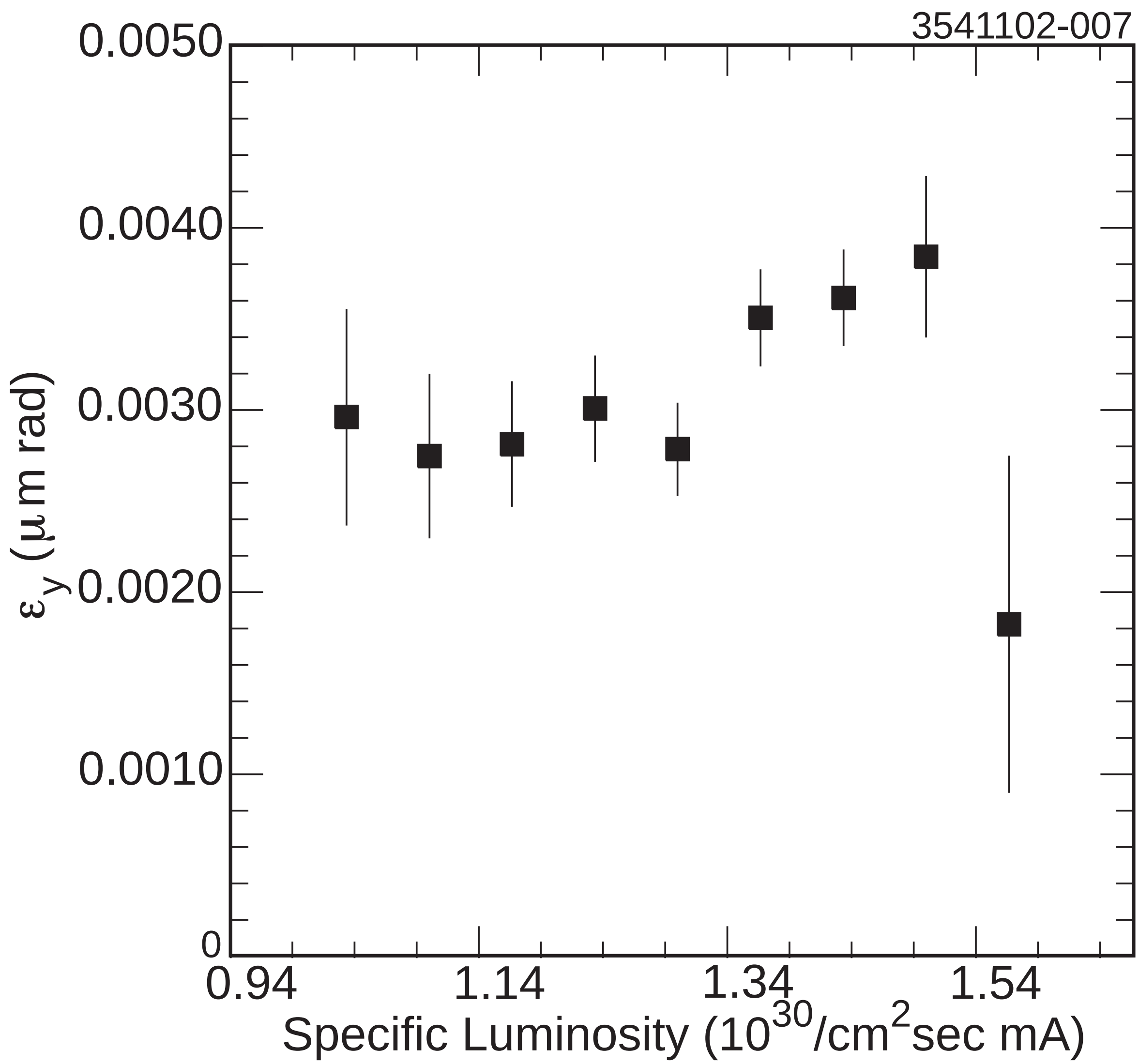

FIG. 7: The extracted vertical emittance as a function of specific luminosity.

is not precise enough to measure the energy spread, $\Delta E/E$ is expected to be smaller than 0.0007 at CESR, resulting in an upper limit of 0.0015 at 90% C.L. for this data.

We have developed methods of measuring the emittances and betas of colliding e^+e^- beams in a non-destructive manner. The method depends on a very good understanding of the resolution of a charged particle tracking system observing the collision region. We demonstrate the methods using $e^+e^- \to \mu^+\mu^-$ events from the luminous region of CESR at the CLEO interaction point. We extract the beam parameters β_x^* and ϵ_x as functions of bunch current and and ϵ_y as a function of specific luminosity. The observations agree with our expectations and with measurements made by other methods. No dynamic effects are observed, although the data for ϵ_y are suggestive of an increase in the emittance with specific luminosity.

---

[1] J.T.Seeman, page 559-562 in "Handbook of Accelerator Physics and Engineering," Chao and Tigner, World Scientific, 1998.

[2] D. Cinabro, K. Korbiak, R. Ehrlich, S. Henderson, and N. Mistry, "Novel Method of Measuring Electron Positron Colliding Beam Parameters", *Nucl. Instrum. Meth.* A481, (2002): 29-35.

[3] S.B. Peck and D.L. Rubin, "CESR Performance and Upgrade Status," *Proceedings Particle Accelerator Conference 1999*, 285.

[4] Y. Kubota, *et al.* (CLEO Collaboration), Nuclear Instruments and Methods, **A820**, 66 (1990); T.S. Hill, Nuclear Instruments and Methods in Physics Research, **A418**, 32, (1998).

[5] D. Cinabro *et. al.* "Observation of the Dynamic Beta Effect at the Cornell Electron-Positron Storage Ring with the CLEO Detector", *Phys. Rev.* E57 (1998): 1193.

[6] A. Anastassov *et al.* (the CLEO Collaboration), "First Measurement of $\Gamma(D^{*+})$ and Precision Measurement of $m_{D^{*+}} - m_{D^0}$", *Phys. Rev.* D65, (2002), 032003.